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## Processing of technogenic formations within the framework of the formation of a circular economy

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### Abstract

**Relevance.** Formation of a circular economy assumes a special place among the new realities that fundamentally affect new technological trends in industrial development. Although the concept of this economy is at the stage of formation, many developed countries, primarily the EU countries, necessarily include it in the most important strategic documents for the development of their countries provisions related to the key principles of a circular economy. The strategic planning system in Russia also includes documents based on the use of individual principles of this economy, contains the development and use of possible mechanisms for integrating the requirements of low-waste and low-carbon development into a circular economy. The industrial development of the country has a special influence on the process of transformation of a linear economy into a circular one, the greening of which is largely associated with solving the problem of processing industrial waste. The decisive role in their formation belongs to the country's mining and metallurgical complex. To date, numerous technological processes for the complex processing of technogenic resources have been developed; there are investment projects in this area. However, there is no modern methodological toolkit for assessing their effectiveness, taking into account the sharply changing world and national conditions, economic conditions.

**The purpose of the work** is to form a methodological approach to assessing the ecological and economic efficiency of processing technogenic formations of mining and metallurgical industries.

**Methods of research.** The methodological basis of the study is a functional approach that allows taking into account the rapidly changing economic conditions. The research methodology is based on the basic provisions of the methodology of real options.

**Results.** A comparative assessment of the formation and processing of wastes from mining and metallurgical production in Russia and the Urals is carried out. A methodological approach to assessing the socio-economic efficiency of processing technogenic resources has been formed. A classification system for the conditions of real options is proposed for assessing the efficiency of processing of technogenic raw materials.

**Conclusions.** The results of the study confirm the feasibility of using the proposed methodological toolkit for assessing the efficiency of processing technogenic resources of various industries. The formed system of classification of the conditions of real options for assessing the efficiency of processing of technogenic raw materials creates the possibility of choosing optimal management decisions.

**Keywords:** circular economy, mining and metallurgical production, waste, technogenic formations, best available technologies, methodological tools, environmental and economic efficiency, classification of conditions of real options.

### Introduction

The defining trend of world development is the increasingly significant role of industry in shaping the modern economy. A full-fledged industrial complex is not only a complete line of national industrial production, which makes it possible to provide society and the activities of the state with everything necessary for its successful functioning. The new reality recognizes scientific rationality as the most important component of modern civilization; it makes it possible to expand the boundaries of the

industrial complex. Within their framework, it becomes possible to include not only the production of industrial products and consumer products, the production of such universal products as energy and information but the production of public and collective goods as well [1, 2]. This actualizes the problem of interdependent development of such spheres as economy, industry, ecology, society. Taking into account this mutual influence, the most important technological trends, new development

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paradigms and conceptual views are formed today; they are based on the key principles of the circular economy [3–5].

The concept of a circular economy (CE), found on its well-known 10 principles (the so-called 10R)<sup>1</sup>, is based on the implementation of the development paradigm, which allows to reduce the ecological footprint of industrial activity [6]. For this purpose, it is necessary to reduce the consumption of raw materials, minimize waste generation, reuse the produced product, organize large-scale recycling of resources, i.e. recycling, etc. [7]. It can be emphasized that three principles of circular economy (10R), are directly related to deeper, non-waste recycling of natural resources – Reduse, Reuse, and Recycle. Compliance with these principles is the framework for the formation of an eco-industrial system, within the territorial framework of which so-called “dome products”<sup>2</sup> are formed due to the sequential processing of technogenic raw materials.

Almost all modern strategies and programs focused on the development of domestic industry as a whole and its individual branches take into account the provisions that require a gradual reduction of maximum permissible limits of environmental pollution. First, this applies to mining and processing activities that form the mining and metallurgical complex. On the other hand, the limited nature of natural resources, the impossibility of replenishing them, intensifies the search for alternative resources that can fully or partially replace traditional natural components. In this regard, there is an increasing interest in man-made raw materials, the processing and use of which not only creates new demanded markets [8, 9], but will also contribute to the restoration of the ecological balance by releasing the land occupied for such waste.

In recent years, there has been an increasing interest in the development of recycling of metallurgical waste, including ferroalloy industries, which, as a rule, are distinguished by a rich composition of components [10, 11]. Nevertheless, today, the volume of processed waste from mining and metallurgical industries has little effect on the rate of their accumulation. A change in the situation can be facilitated by the development of theoretical and methodological provisions that take into account not only the various economic effects and environmental consequences of the involvement of man-made waste in economic activities but the system of possible numerous risks as well. This makes actual the problem of forming a modern methodological apparatus for assessing the ecological and economic efficiency of the processing of technogenic formations.

**Greening of industrial development in Russia.** As already noted, the most important new realities that fundamentally affect the development of the industry are gaining strength of the concept of a closed-loop economy, a circular economy, a green economy, etc. Despite the individual features of interpretation of these terms, their common feature is the defining significance of greening of the industry. At the same time, greening should permeate not only the processes associated with a new

industrialization of the domestic economy but with the formation of a new eco-style of life as well, with an increase in the environmental responsibility of an individual, business, and the state as a whole. The urgency of abandoning the modern world model of the linear economy is confirmed by the high probability of doubling the use of material resources (from 92.8 billion tons of resources in 2015 to 186 billion tons in 2050).<sup>3</sup>

The inevitability of the greening process was stated in Russia as early as in the framework of the 2017 “year of ecology” declared in the country. This topic was the subject of discussion at the Russian Investment Forum in Sochi (2017), where the round table “Green Economy as a Vector of Development” aroused great interest. Within the framework of the All-Russian Congress called “Industrial Ecology of Regions” (Yekaterinburg, 2018) the main topics of discussion were waste processing and rational resource use. Even earlier, Russia developed key regulations on the Best Available Technique (BAT), i. e. technologies that are cost-effective and implemented at a number of facilities. At the same time, they should have the lowest level of impact on the environment, allow for resource and energy conservation. These requirements were in the Federal Law “On Amendments to the Federal Law “On Environmental Protection” and Certain Legislative Acts of the Russian Federation”.<sup>4</sup> Three stages have been identified for the transition to a new system of state regulation that determines the transition to BAT: 2015–2018; 2019–2022; 2023–2025. The task of the first stage was the adoption of by-laws in the area of necessary set of measures for BAT; the second was the issuance of integrated environmental permits for new and 300 operating largest enterprises – “polluters”, as well as for all enterprises that applied. At the third stage (by 2025), it is planned to extend the BAT requirements to all large enterprises belonging to category I facilities. The transition to BAT is not only a long-term but an extremely investment-intensive process as well. The total volume of necessary investments, according to the Ministry of Industry and Trade of the Russian Federation, is 8.22 trillion rubles, and taking into account investments in the modernization of industries that are not related to the areas of application of BAT according to the regulations of the ministry, such as crop production, etc., this amount rises to 13.6 trillion rubles. Almost half of the investment required for the transition to BAT (about 43% of 8.22 trillion rubles) is the investment required for such a transition in the mining and metallurgical complex (MMC), as well as for creating a waste management system. This largely led to allocation of a special federal project called “Implementation of the best available technologies” within the framework of the National project “Ecology”, which unites 11 federal projects. It is for the implementation of this project that the largest funds are allocated (60%) – 2.4 trillion rubles from the total project budget of 4.0 trillion rubles (intended for 6 years).

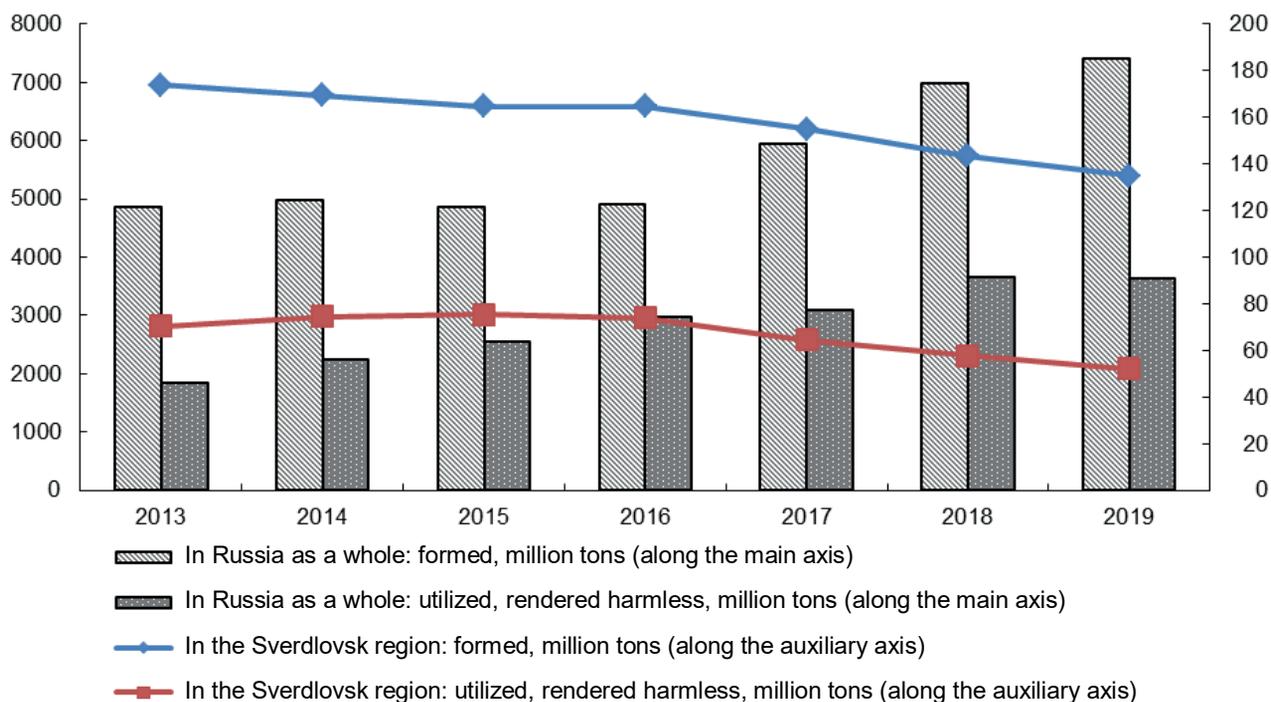
**Man-made waste from the mining and metallurgical complex.** The main source of industrial waste accumulation

<sup>1</sup>Refuse (refusal), Rethink (revision), Reduse (reduction), Reuse (reuse), Repair (repair), Refurbish (modernization), Remanufacture (reconstruction), Repurpose (repurposing), Recycle (recycling), Recover (restoration).

<sup>2</sup>“Dome products” are production wastes generated in one enterprise that can serve as a factor in the production of another enterprise.

<sup>3</sup>United Nations Environment Programme (UNEP) and International Resource Panel (IRP). ‘International Resource Panel Report – Resource efficiency: potential and economic implications’, March 2017, 330 p. URL: [http://www.resourcepanel.org/sites/default/files/documents/document/media/resource\\_efficiency\\_report\\_march\\_2017\\_web\\_res.pdf](http://www.resourcepanel.org/sites/default/files/documents/document/media/resource_efficiency_report_march_2017_web_res.pdf)

<sup>4</sup>On amendments to the Federal Law «On Environmental Protection» and certain legislative acts of the Russian Federation (with amendments and additions dated July 26, 2019): Federal law of 21.07.2014, No. 219-FZ.



**Figure 1.** Volumes of formation, utilization and neutralization of wastes of the mining and metallurgical complex of the Sverdlovsk region and Russia as a whole for 2013–2019 (data for the Sverdlovsk region for 2019 are preliminary; the forecast is formed taking into account the trend). Compiled by authors on the basis of statistical indicators “Generation of production and consumption waste by types of economic activity (according to OKVED and OKVED2 (Russian National Classifier of Types of Economic Activity))” and “Utilization and disposal of production and consumption waste by types of economic activity (according to OKVED and OKVED2)” of the Federal State Statistics Service, as well as data of State reports “On the state and protection of the environment of the Sverdlovsk region” for 2017–2018.

**Рисунок 1.** Объемы образования, а также утилизации и обезвреживания отходов горно-металлургического комплекса Свердловской области и России в целом за 2013–2019 гг. (данные по Свердловской области за 2019 г. являются предварительными, прогноз сформирован с учетом тренда). Составлено авторами на основе статистических показателей «Образование отходов производства и потребления по видам экономической деятельности (по ОКВЭД и ОКВЭД2)» и «Утилизация и обезвреживание отходов производства и потребления по видам экономической деятельности (по ОКВЭД и ОКВЭД2)» Федеральной службы государственной статистики, а также данных Государственных докладов: «О состоянии и об охране окружающей среды Свердловской области» за 2017–2018 гг.

are enterprises related to the type of economic activity called “mining”. According to the state report “On the state and protection of the environment of the Russian Federation”, the volume of production and consumption waste generated for this type of activity in 2019 was estimated at 7257 million tons, which is 93.6% of the total volume of waste generated in the country. First, this is a waste of overburden rock. In 2018, this indicator was at the level of 6850.5 million tons. The volume of disposed and neutralized waste of domestic mining enterprises in 2019 was estimated at 3,561.6 million tons. Mining companies account for 52.3 % of the waste used for processing and recycling. In 2019, investments in the industry aimed at strengthening environmental protection were estimated at 40.2 billion rubles. At the same time, the costs of protecting the environment from the activities of organizations involved in the extraction of minerals amounted to 57 billion rubles. (53 billion rubles 2018).

In comparison with the types of activities related to the extraction of minerals, the volume of generated and accumulated waste from metallurgical production is substantially lower. Nevertheless, despite the annual tightening of measures to preserve environmental safety, the metallurgical industry remains one of the main sources of air pollution and surface water bodies. The volume of production and consumption waste

generated in the framework of the kind of activity called “metallurgical production and production of finished metal products” in 2019 was estimated at 156.7 million tons. At the same time, the volume of used and neutralized waste of this kind of activity amounted to 77.1 million tons (49% of the level of formation). The costs of environmental protection of organizations of metallurgical production and production of finished metal products are comparable and even slightly exceed the costs of enterprises engaged in the extraction of minerals. They were estimated in 2019 at 57.5 billion rubles.

In fact, all major Russian mining and metallurgical plants regularly carry out environmental protection measures. One of the most important measures implemented in 2018 at the enterprises of the domestic mining and metallurgical complex is the construction of an aspiration system at PAO MMK in Magnitogorsk, which would reduce dust emissions by 600 tons per year. NLMK has completed the reconstruction of an aspiration unit at its production site in Lipetsk, which will reduce over 90% of dust emissions in the refractory workshop of the plant. Compared to existing furnaces, a new unit reduces emissions by 2.5 times. In 2018, a modern dust collection unit was put into operation in the blast-furnace smelting shop at AO EVRAZ Nizhny Tagil Metallurgical Plant, and similar units were repaired in the coke, coal preparation, wheel-banding,

blast-furnace, converter and other shops. The implemented measures allowed to reduce air emissions by 0.38 thousand tons. A gas-cleaning installation for electric ore smelting furnaces was debugged at OOO RUSAL Kremniy Ural, which made it possible to reduce emissions into the atmosphere by 3.4 thousand tons; and repair of dust separation equipment and smoke exhausters in workshops agglomeration and pellets at EVRAZ Kachkanar Mining and Processing Plant JSC – emissions were reduced by 1.8 thousand tons.

In 2019, investments in fixed assets aimed at environmental protection and rational use of natural resources of enterprises of the mining and metallurgical complex of the Russian Federation increased by 110% compared to the previous year, amounting to 75.6 billion rubles. In 2019, a total of 32.1 million tons of mining waste, including 8.1 million tons of metal ore mining waste, was disposed of, neutralized and buried at domestic enterprises and landfills.

One of the most powerful mining and metallurgical complexes in the Russian Federation is located in the Middle Urals. The share of ferrous and non-ferrous metals in the structure of waste from the processing industries of the Sverdlovsk region is about 90%. In the total volume of production and consumption waste, the share of waste from mining and metallurgical industries in 2018 amounted to 95.6%. The nature of changes in the volume of formation, as well as the utilization and disposal of waste from the mining and metallurgical complex of the Sverdlovsk region and Russia as a whole in recent years, is different (Fig. 1). If the dynamics up to 2018 forms a trend of growth in the formation, utilization and disposal of waste at the federal level, then the opposite is true for the Middle Urals.

According to the report on the environmental situation in the Sverdlovsk Region in 2018, the volume of accumulated waste in the region in the reporting year amounted to almost 9.39 billion tons, which is 18 million tons more than in the previous year. At the same time, the share of industrial waste in the total waste at the end of 2018 was 99.1% (9.31 billion tons). In the region for the period from 2013 to 2018, there was a decrease in the volume of production waste from 194.2 to 154.9 million tons, including waste of I-IV hazard classes – it was estimated at 6.11 million tons (3.9%), which is 36.4% less than in 2013 (9.62 million tons). This is primarily due to their partial processing. The main share of waste of these hazard classes by mass is made up of ferroalloy slags, slags produced in steel, copper, coke, etc. The volume of accumulated waste of organizations of the mining and metallurgical complex of the Sverdlovsk region in 2018 amounted to almost 8.8 billion tons.

If the share of enterprises in the Middle Urals is 2% in terms of the formation of pollutants by enterprises of the mining and metallurgical industry of the Russian Federation (according to data for 2018), then in terms of investment in fixed assets it was 3.7% in 2018, and 7.9% in 2019. In 2019, almost 6 billion rubles were invested in environmental protection and rational use of natural resources by enterprises of the mining and metallurgical complex of the Sverdlovsk region, which is more than twice the level of the previous year (236.4% by 2018).

**The formation of the market of products based on man-made structures.** The involvement of technogenic raw materials in production becomes one of the most promising directions for the development of metallurgical production. Such raw materials are a new source of raw materials, and in

addition, their processing helps to reduce the burden on the environment. This direction of technological development not only expands the raw material base. It is the first step towards the formation of a circular economy [12]. Within the framework of the ideology of a circular economy, the importance of recycling becomes actual. There is an opportunity to form a full-fledged market for domed products [13–15]. However, the country's mining and metallurgical complex continues to have significant barriers to the formation of elements of circular development in the domestic economy. Even modernized technological processes do not provide the required level of environmental safety. The operation of mining and metallurgical enterprises still leads to the formation of numerous production wastes, various in terms of volumetric indicators, composition, degree of hazard, disposal possibilities, etc. At the same time, according to experts, the development of the technological base of the circular economy within the framework of metallurgical production will reduce the carbon footprint from the activities of ferrous metallurgy enterprises by 2–3 times [16].

However, despite the importance of reducing the environmental burden within the territory of metallurgical enterprises, the rational use of additional sources of expanding the mineral resource base is increasingly important. Technogenic resources of the Urals are unique in their complex composition. They contain a number of elements necessary for the development of traditional and high-tech industries. One can also note an increasing deficit of metals of large and low-tonnage groups (boron, manganese, copper, molybdenum, niobium, etc.), which are contained in man-made resources, primarily in slags, sludge and dust of metallurgical and ferroalloy industries.

In the Middle Urals, the processing of the formed slags is carried out in full, which is facilitated by the presence of high-power plants for their processing at all factories of the region [17]. Separate large plants have already set up the development of existing dumps. Multicomponent composition of waste slags of the region is of interest, which makes them in demand for processing in order to obtain a number of metals important for industry.

## Results

### **Methodical approach to assessing the ecological and economic efficiency of processing technogenic formations.**

The transition of enterprises of the mining and metallurgical industry to the technology of waste-free production is a priority task but it is not feasible in the next few decades. The existing technological base allows manufacturers to minimize the amount of waste generated to certain limits. However, the possibility of processing technogenic wastes of metallurgical production, extracting valuable components from them is determined by a system of physical and chemical criteria, technological features of the treatment processes, environmental requirements, as well as economic feasibility.

The assessment of ecological and economic efficiency of the processing of technogenic raw materials is influenced by many factors, the consideration of which depends on the task at hand. Allocation and systematization of such factors allows us to form a step-by-step methodological approach to assessing the ecological and economic efficiency of processing man-made resources. The directions of research are systematized according to the setup diagram principle (Fig. 2).

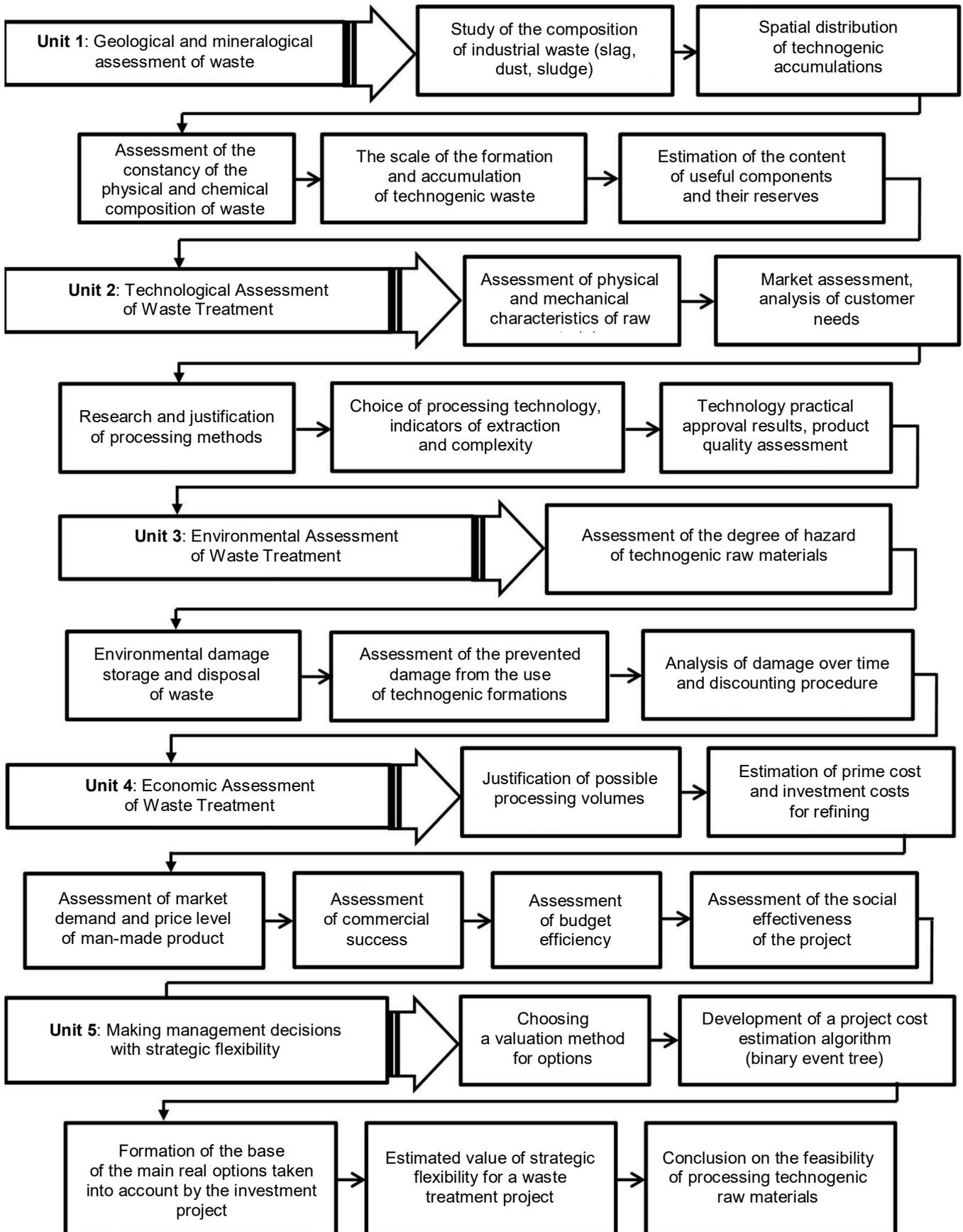


Figure 2. Setup diagram of a methodological approach to assessing the ecological and economic efficiency of processing technogenic resources. Compiled by the authors.

Рисунок 2. Блок-схема методического подхода к оценке эколого-экономической эффективности переработки техногенных ресурсов. Составлено авторами.

The first unit includes the results of geological and mineralogical studies of waste. They take into account the data of the composition of formations (slag, dust, sludge), the physical and chemical constancy of its structure, the scale of formation and remoteness of waste accumulations from the place of consumption (customer), the content of useful components and their reserves. Further, the technological capabilities for processing a technogenic resource are determined (unit 2), including the physical and mechanical characteristics of raw materials, the availability of a technological base, etc. When justifying the choice of a technological scheme, the results of market assessment and demand analysis are taken into account. Within the framework of the third unit, an environmental assessment of waste is carried out, which includes an assessment of the degree of danger of the used technogenic formations, calculation of damage as a result of storage, disposal and processing of waste, as well as the prevented damage from their use and (or) processing. At this stage of the study, the change in environmental damage over time is assessed and a discounting procedure is carried out.

The assessment of public effectiveness carried out within the fourth unit is based on the effect (positive or negative) obtained as a result of the project's impact on the social and environmental system. The multiplier effect of the project for the processing of industrial waste on other sectors of the economy is also taken into account. Evaluation of the social efficiency of the processing of man-made waste from mining enterprises is carried out by comparing the production costs of a new man-made product with traditional products that have proven their effectiveness at the level of related industries, where such products of comparable consumer properties are used. It can be noted that the implementation of BAT principles can have a significant positive impact on the social efficiency of projects in the field of processing technogenic resources.

The methodology for evaluating the effectiveness of investment projects takes into account a number of traditional methods, including the income capitalization method, the net assets method, the analogous company method, etc. Nevertheless, to assess the efficiency of processing man-made waste, it is advisable to adhere to approaches that take into account a comparative assessment of a new man-made product with a traditional one, as well as an estimate of the discounted cash flows of the project, which makes it possible to predict their expected future value. However, the main drawback of the data obtained on the basis of the assessment of discounted cash flows is that only the basic parameters of the project implementation are taken into account, which are not enough in a rapidly changing environment. In this regard, this approach to valuation can be supplemented with elements of strategic flexibility based on the method of real options [18]. The evaluation of the strategic flexibility of design solutions for the processing of technogenic products is laid down in the fifth unit of the scheme.

A real option represents the right but not the obligation of its owner to perform any transactions with assets in the future. One of the main issues while working with real options is the choice of a model for setting their price. The most common methods for assessing the value of options include the Black–Scholes model modified for the real sector of the economy and the binomial model, also called (after its authors) the

Cox–Ross–Rubinstein model. The main difference between these models is the time factor. The Black–Scholes model is continuous, while the binomial method is discrete and requires information on a finite number of intervals, on the basis of which a binary tree is constructed [19].

**Evaluation of the efficiency of processing technogenic formations based on the methodology of real options.** The method of real options has been widely tested in the Ural metallurgy when choosing effective solutions in the processing of technogenic raw materials. For example, the development of real options was carried out to determine the effectiveness of implementation of a promising metallurgical technology for obtaining a new boron-containing ferroalloy for microalloying steel that meets the criteria of the best available technologies [20]. The cost of the project, taking into account the conditions of strategic flexibility based on real options, amounted to 80.3 million rubles, while the share of the increase in the value of the project with flexibility was 79% of the indicated amount.

As part of the modernization of the Russian zinc industry, an interesting result was achieved by the authors of the project for assessing the effectiveness of the integrated use of technogenic raw materials based on the method of real options. Under the conditions of existing production facilities, a forecast of possible volumes of technogenic zinc-containing raw materials suitable for processing and extraction of demanded non-ferrous metals was formed [21]. The cost of the project's strategic flexibility was estimated at 722.5 million rubles with the base cost of implementing plans for the processing of man-made zinc-containing raw materials 73.2 million rubles.

Significant works also include evaluating the effectiveness of the project for the production of ligatures with rare earth metals based on existing ferroalloy plants in the Urals. Recognition of strategic flexibility made it possible to increase significantly the value of the project compared to the basic one. Net discounted income, including the value of options, was 68.2 million rubles. Thus, due to the use of the real options method in calculations, the economic feasibility of producing REM-containing ferroalloys was determined [22].

**Formation of a classification system for the conditions of real options.** The use of real options involves recognition of variability of the project parameters, which does not cover the basic scenario of its implementation. Previous studies [18] allowed forming a methodological approach to determining the ecological and economic efficiency of processing technogenic formations, within which the expediency of assessing the strategic flexibility of technological decisions based on the method of real options was substantiated. This method is universal; nevertheless, embedding its elements into the valuation model for each individual project creates a system of scenarios (real options) that is unique in its structure [23, 24].

Analysis of the practice of mastering technologies for processing man-made formations by mining enterprises, successful testing of the approach proposed by the authors to determine the effectiveness of this process based on the method of real options allowed us to form a classification system for the conditions of real options to assess the efficiency of processing man-made waste from mining and smelting companies. In the proposed classification system, the conditions corresponding to real options are generated according to the main criteria that determine the project parameters (table). Therefore, when

**Classification system for the main conditions of real options by parameters of investment projects\*.****Система классификации основных условий реальных опционов по параметрам инвестиционных проектов\*.**

<i>Project parameters that define the conditions for its implementation</i>			
a. Internal factors	a.1. Technical and technological capabilities	a.2. Availability of funds	a.3. Enterprise development strategy for the medium and long term
b. Environmental factors	b.1. Geopolitical risks	b.2. Economic risks	b.3. Risks of emergency situations
c. Market condition	c.1. The market situation is unstable. Downward trend in demand and/or prices	c.2. Market conditions are stable	c.3. The market situation is unstable. Trend to increase in demand and (or) prices
d. Environmental risks	d.1. Radiation activity	d.2. The area occupied by dumps	d.3. Harm to health and the environment
<i>Classification conditions of real options formed on the basis of the selected parameters</i>			
I. Resource flexibility	I.I. Change in the structure of manufactured metal products, diversification of the production line of an enterprise	I.II. Refusal to smelt a metal-source of technogenic formation	I.III. Replacement of raw materials for smelting metal, or a change in the technology used, which changes the quality characteristics of waste (slag, sludge, dust)
II. Product flexibility	II.I. Change in technology for processing technogenic raw materials	II.II. Changes in the quality characteristics of products obtained from technogenic raw materials	II.III. Changing the structure of the final product from technogenic raw materials
III. Project scale	III.I. Expanding the scope of the project	III.II. Reducing the project scale	III.III. Stop the implementation of the project
IV. Project implementation time	IV.I. Setting the start time of the project	IV.II. Assigning the stages of project implementation	IV.III. Suspension of project implementation

\*Compiled by the authors.

a certain event occurs, which is formed by a set of parameters, including the characteristics of the enterprise, environmental factors, market conditions, and environmental reliability, the project implementation conditions that model the corresponding real option change. This approach to the formation of real options allows you to take into account the main parameters and changing conditions for the implementation of the project, which determines the choice of management decisions.

The project parameters highlighted in the upper part of the table form a matrix of attributes (a.1.,..., d.3.), the elements of which set the criteria for classifying the project implementation conditions from the lower part of the table (I.I.,..., IV.III.). Relevant parameters include the internal factors of the project implementation at an enterprise, including the determination of technical and technological capabilities, the availability of free funds that allow activating options deviating from the baseline conditions of the project without delay, the stability of the market situation, the risks associated with the environmental safety of the waste processing scheme of the MMC and other factors.

Considering that environmental conditions is especially relevant for projects aimed at exporting products obtained from processed man-made waste, as well as those implemented during the period of negative effects (in particular, distribution of virus diseases on a global scale). The pandemic is an event of force majeure, which puts it on a par with natural disasters, the damage from which should be compensated by the state. Nevertheless, given the scale of the coronavirus pandemic in 2020 and its consequences for business, the risk of resumption

of self-isolation measures may significantly increase the cost of implementing investment projects in the near future.

The classification signs formed on the basis of the selected parameters determine the conditions to which the investment project implementation plan should be adapted in order to obtain the greatest benefit, or to minimize losses. Moreover, the proposed approach allows you expanding the base of real options, maximally adapting the project to the real conditions of its implementation. Usually, the implementation of new technological solutions in the industry is limited to 7–9 real options, however, the proposed system in the given form allows you to generate 12 options.

A mechanism for generating real options can be built into the formed classification system for the conditions of real options to assess the efficiency of processing industrial waste. It selects conditions that correspond to the input parameters of the project (a.1.,..., d.3.). The system of conditions formed in this way creates a kind of passport of a real option, according to which the price of its activation is calculated. A similar mechanism can be implemented on the basis of the methodological apparatus of neural network modeling, which is widely used in problems of classification and pattern recognition. This approach determines the possibility of choosing management decisions and can be implemented in practice in the form of a computer program. The development of the described mechanism will act as a priority task for further research in this area.

The mode of operation of the mechanism can be demonstrated in the following example. The published forecast for the development of key metal ores in the world, for example, for

the ferroalloy industry, becomes the reason for the revision of the production policy of companies working in this area for the near future. The planned diversification should take place in two months, while the launch of the investment project is expected in the coming days. At the same time, the scheme of production of a new ferroalloy in the shop differs from the current one only in the composition of the feed. In this situation, all other things being equal, the project parameters in the classification system (table) should be adjusted relative to point a.3. "Development strategy of an enterprise for the medium and long term". The implemented model for evaluating the effectiveness will have to activate a real option, which corresponds to the following classification characteristics: I.III.; II.III.; III.0.<sup>1</sup>; IV.II. In this case, the calculation of the option value will take into account the possible lost or acquired profit from the replacement of produced ferroalloy products, changes in the cost of charge materials, electricity, etc.

Choosing the best option for waste management, whether it is recycling or recovering, allows you to solve problems such as releasing the land they occupy and reducing the impact on the land of harmful substances contained in the waste that determines the income generated as a result of prevented environmental damage. It is equally important to solve the problem of expanding the raw material base. In addition, the adoption of an industry-specific methodology for assessing the costs of organizations' transition to BAT principles taking into account by the national project "Ecology", will allow counting on incentives in the form of tax benefits (deductions), accelerated

depreciation of fixed assets, or the use of funds spent on the introduction of BAT as a calculation for damage to the environment. These provisions may be included in the proposed classification system for the conditions of real options.

### Conclusion

The conducted research allows us to consider the processing of technogenic formations as the initial stage of the transition to a circular economy. Comparative analysis of the generated, utilized and neutralized wastes of the mining and metallurgical complex of Russia and the Central Urals made it possible to determine the multidirectional dynamics of the development of these processes. The methodological approach developed by the authors to assessing the ecological and economic efficiency of processing man-made resources was the basis for the formation of a fairly universal block diagram applicable in the practice of resource-intensive industries. The selected five units of the proposed scheme allow for the geological and mineralogical, technological, environmental and economic assessment of processing of man-made raw materials, as well as to take into account the elements of strategic flexibility of the project. This approach allows you to identify the most appropriate management decisions that meet the conditions of a changing situation. The studies carried out made it possible to form a classification system for the main conditions of real options according to the parameters of investment projects to assess the environmental and economic efficiency of processing industrial waste. The proposed system can be implemented in practice as a computer program.

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<sup>1</sup>Conditions that do not require adjustment remain unchanged; the model elements describing them correspond to the zero level, for example, "III.0."

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# Переработка техногенных образований в рамках формирования циркулярной экономики

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## Аннотация

**Актуальность.** Среди новых реалий, принципиально влияющих на новые технологические тренды промышленного развития, особое место занимает формирование циркулярной экономики. Хотя концепция данной экономики находится в стадии формирования, многие развитые страны, прежде всего страны ЕС, обязательно включают в важнейшие стратегические документы развития своих стран положения, связанные с ключевыми принципами циркулярной экономики. Система стратегического планирования в России также включает документы, основанные на использовании отдельных принципов этой экономики, содержит разработку и использование возможных механизмов интеграции в циркулярную экономику требований малоотходного и низкоуглеродного развития. Особое влияние на процесс трансформации линейной экономики в циркулярную оказывает индустриальное развитие страны, экологизация которого во многом связана с решением проблемы переработки техногенных отходов. Решающая роль в их образовании принадлежит горно-металлургическому комплексу страны. К настоящему времени разработаны многочисленные технологические процессы комплексной переработки техногенных ресурсов, имеются инвестиционные проекты в этой области. Однако современный методический инструментарий оценки их эффективности с учетом резко меняющихся мировой и национальной конъюнктуры, условий хозяйствования отсутствует.

**Цель работы** – формирование методического подхода к оценке эколого-экономической эффективности переработки техногенных образований горно-металлургических производств.

**Методы исследования.** Методической основой исследования является функциональный подход, позволяющий учесть быстро меняющиеся условия хозяйствования. Методический аппарат исследования опирается на базовые положения методологии реальных опционов.

**Результаты.** Проведена сравнительная оценка образования и переработки отходов горно-металлургического производства России и Урала. Сформирован методический подход к оценке социально-экономической эффективности переработки техногенных ресурсов. Предложена система классификации условий реальных опционов для оценки эффективности переработки техногенного сырья.

**Выводы.** Результаты исследования подтверждают практическую целесообразность использования предложенного методического инструментария для оценки эффективности переработки техногенных ресурсов разной отраслевой принадлежности. Сформированная система классификации условий реальных опционов для оценки эффективности переработки техногенного сырья создает возможность выбора оптимальных управленческих решений.

**Ключевые слова:** циркулярная экономика, горно-металлургическое производство, отходы, техногенные образования, наилучшие доступные технологии, методический инструментарий, эколого-экономическая эффективность, классификация условий реальных опционов.

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